National Aeronautics and Space Administration

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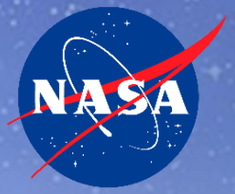

A real-time optical ground receiver for photon starved environments

Free-Space Laser Communications XXXV

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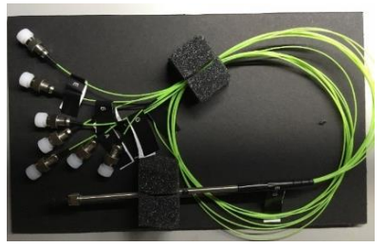
Introduction

- **NASA is using the CCSDS Optical Communications High Photon Efficiency (HPE) waveform on future missions: Optical Artemis-2 Orion (O2O), Psyche**
  - **PPM: 4, 8, 16, 32, 64, 128, 256**
  - **Slot widths: 512 ns - 125 ps**
  - **Maximum data rate: ~2 Gbps**
- **NASA Glenn is building a photon-counting ground receiver compliant with the CCSDS Optical Communications HPE standard**
  - **PPM: 16, 32**
  - **Slot widths: 2 ns, 1 ns, 0.5 ns**
  - **Maximum data rate: 267 Mbps**
- **Goals:**
  - **Utilize commercial off the shelf (COTS) components**
  - **Demonstrate with O2O at the NASA Goddard Low Cost Optical Terminal (LCOT) ground station**
  - **Transfer technology to commercial company**

Receiver Subsystems Under Development

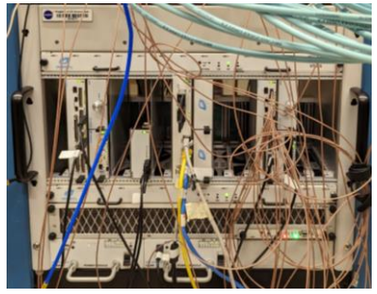


Fiber Interconnect:

- Photonic lantern (one multimode fiber input to 7 FMF outputs) or FMF
- Input fiber core size, number of outputs, and output fiber core size scalable to application
- In house prototyping capability; development partnership with University of Sydney

Single Photon Detector:

- COTS detectors, portable, rack-mounted
- Array of FMF coupled single-pixel detectors sharing one cryostat or single monolithic 16-channel array
- Continuous operation, includes amplifier electronics, 60-80% efficient



FPGA-based Receiver:

- 1 ADC per detector channel; digital detector channel combining
- Real Time processing; COTS development platform
- Compatible with CCSDS downlink optical waveform (high photon efficiency)
- FPGA VHDL/Verilog receiver code will be released

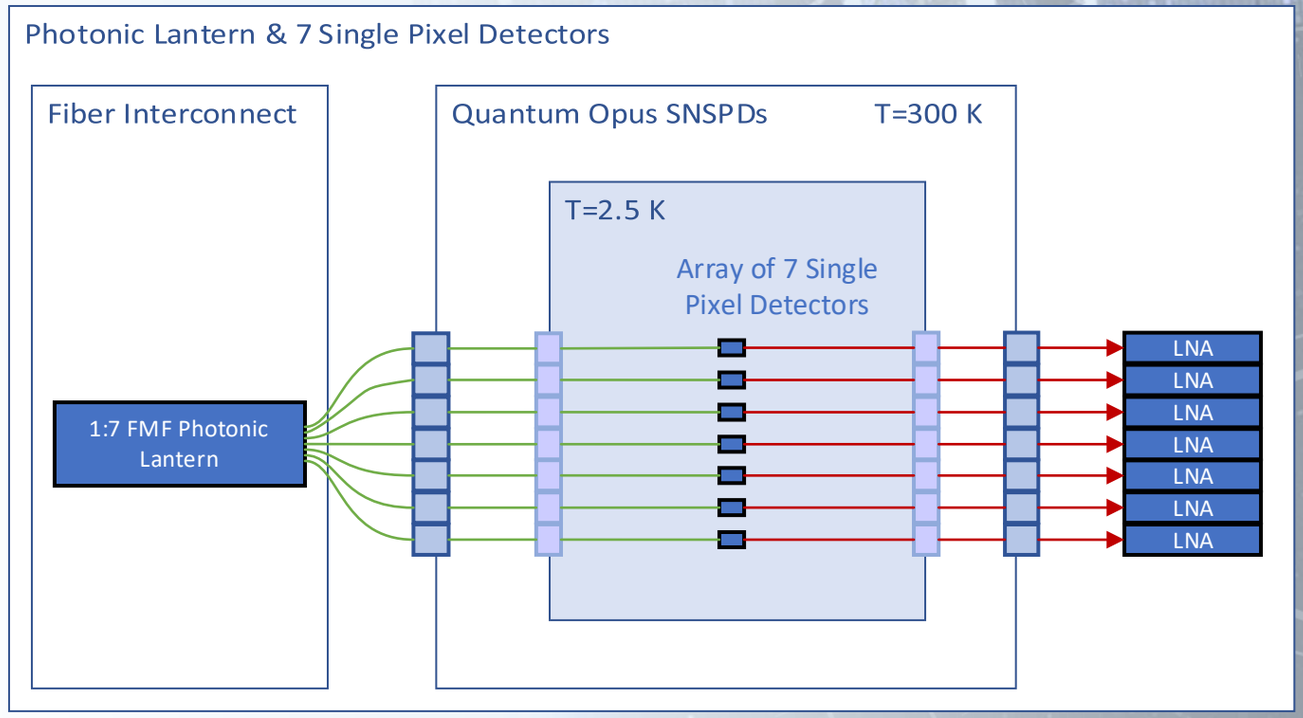
Fiber Interconnect and Detectors:
Photonic Lantern + 7 Single Pixel Detectors

Photonic Lantern:

- **FMFs:**
  - 20 um graded-index core
  - NA: 0.19
  - 6 LP-modes
- **MMF input:**
  - 55 um
  - 42 total modes

Detectors:

- **Efficiency: 80-82%**
- **Dark count rate: 3 kcps**
- **Rise time: 850 ps**
- **1/e reset time: 15 ns**
- **Jitter: 60-80 ps FWHM**



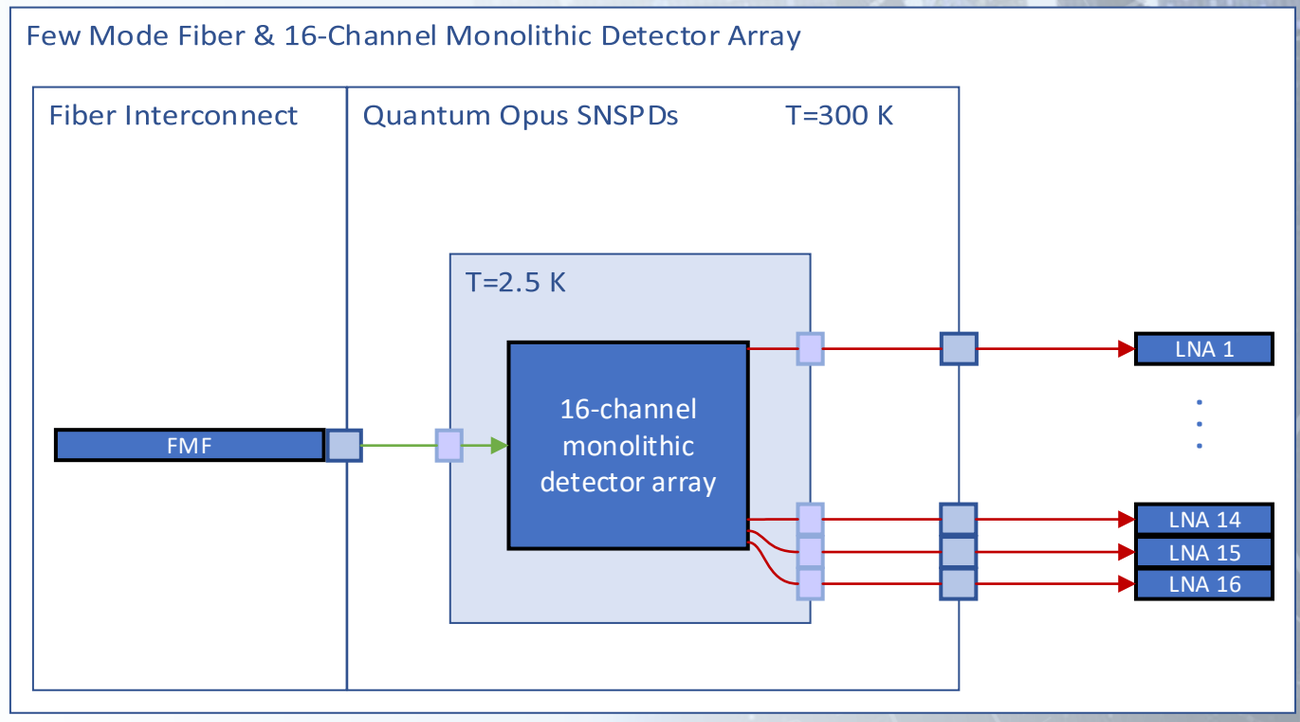
Fiber Interconnect and Detectors:
FMF + 16-Channel Detector Array

FMF:

- **20 um graded-index core**
- **NA: 0.19**
- **6 LP-modes**

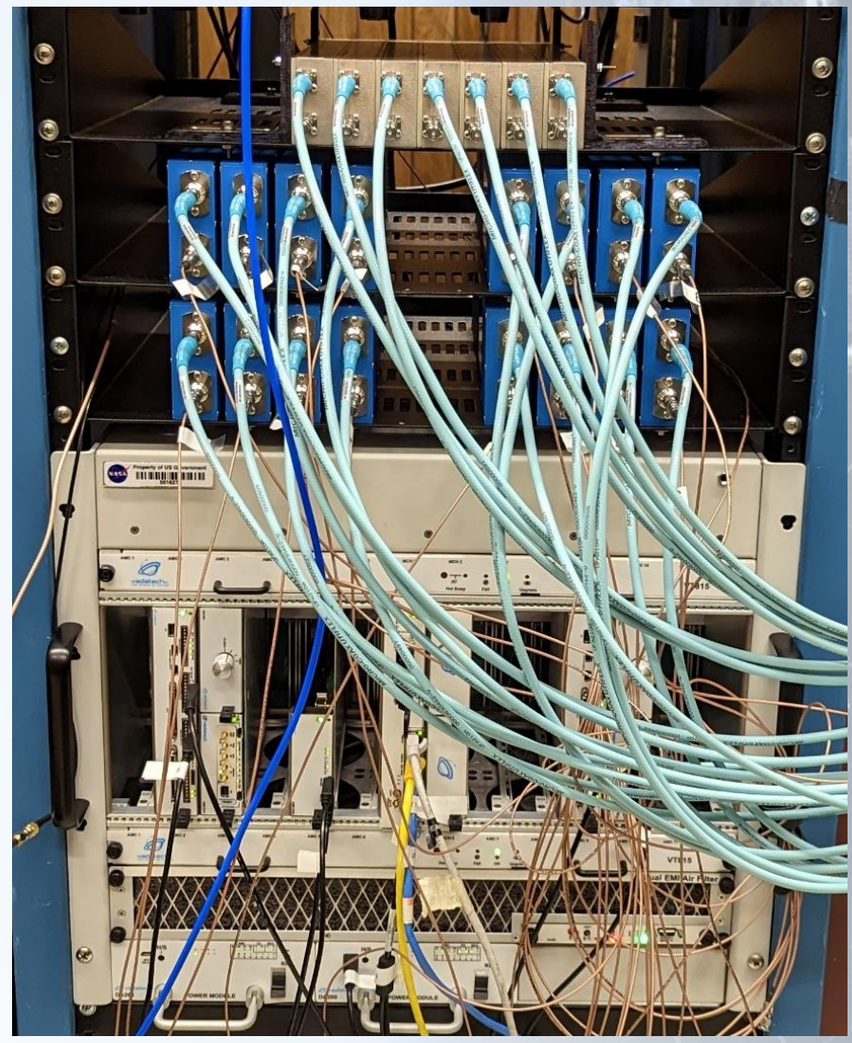
Detectors:

- **Efficiency: 83%**
- **Dark count rate: 3-10 kcps**
- **Rise time: 500 ps**
- **1/e reset time: 5-8 ns**
- **Jitter: 75-95 ps FWHM**

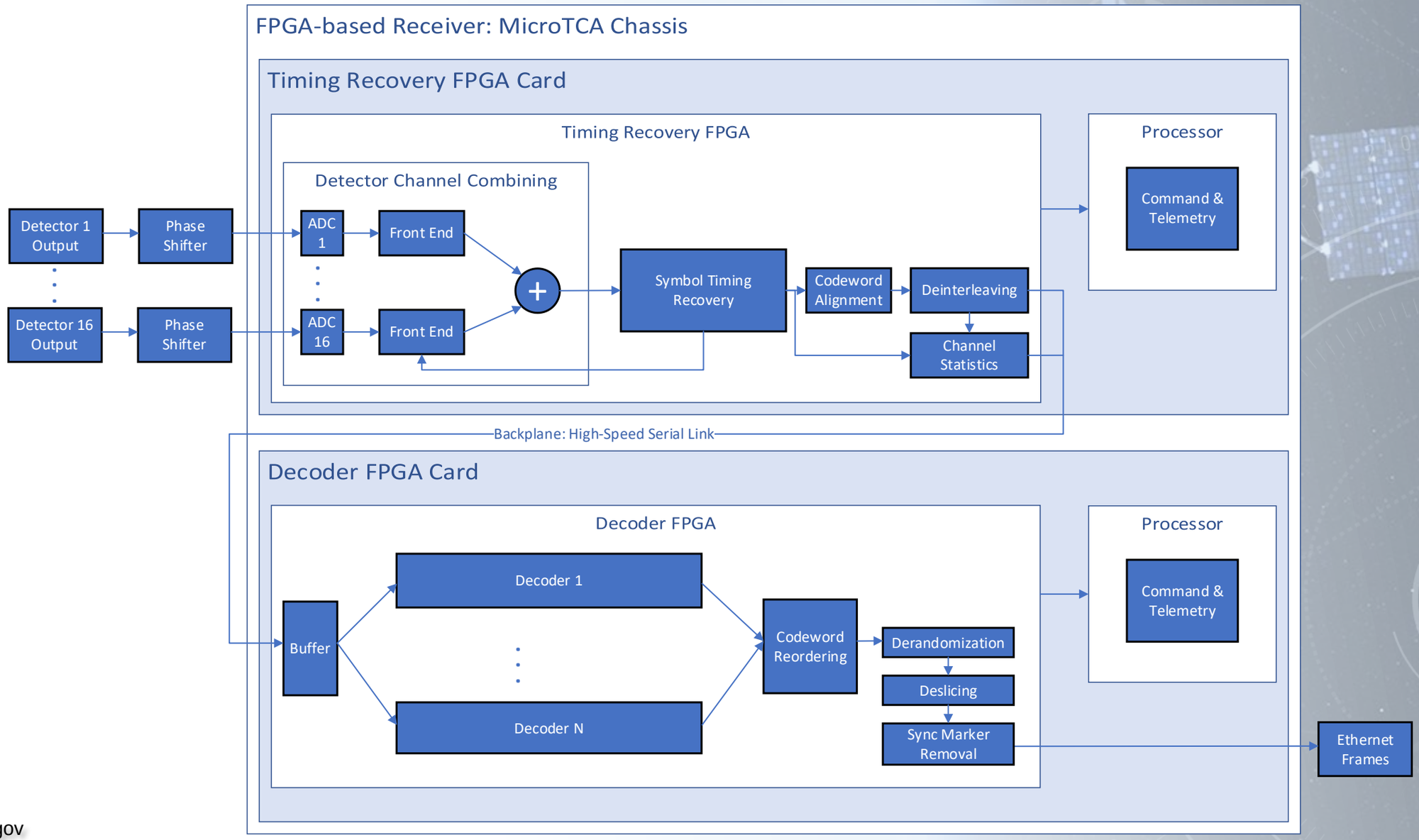


FPGA-based Receiver

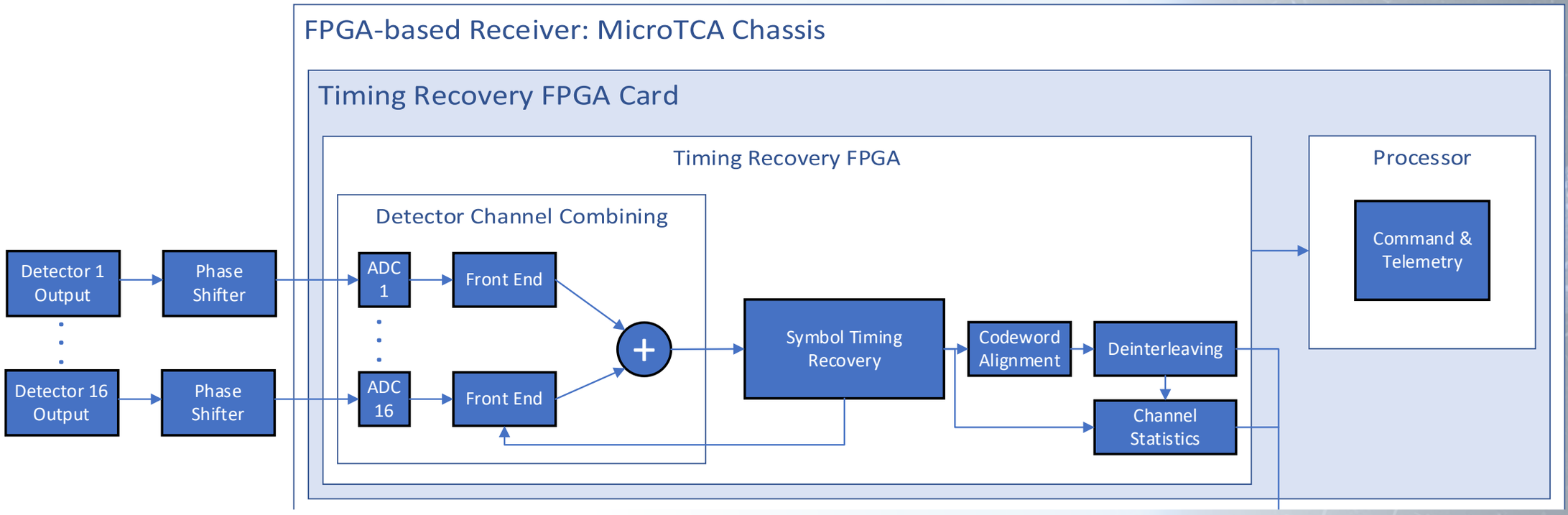
- COTS MicroTCA development platform
- Command/telemetry interface is through HTTP interface built on Space Telecommunications Radio System Architecture



FPGA-based Receiver



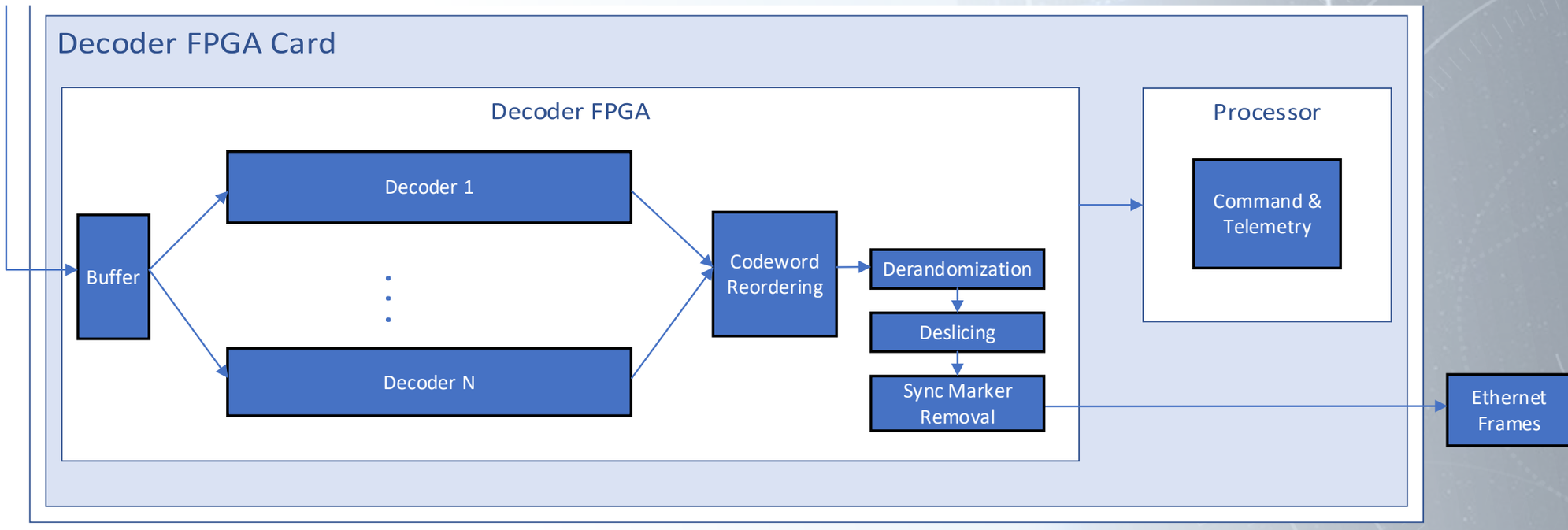
Timing Recovery FPGA



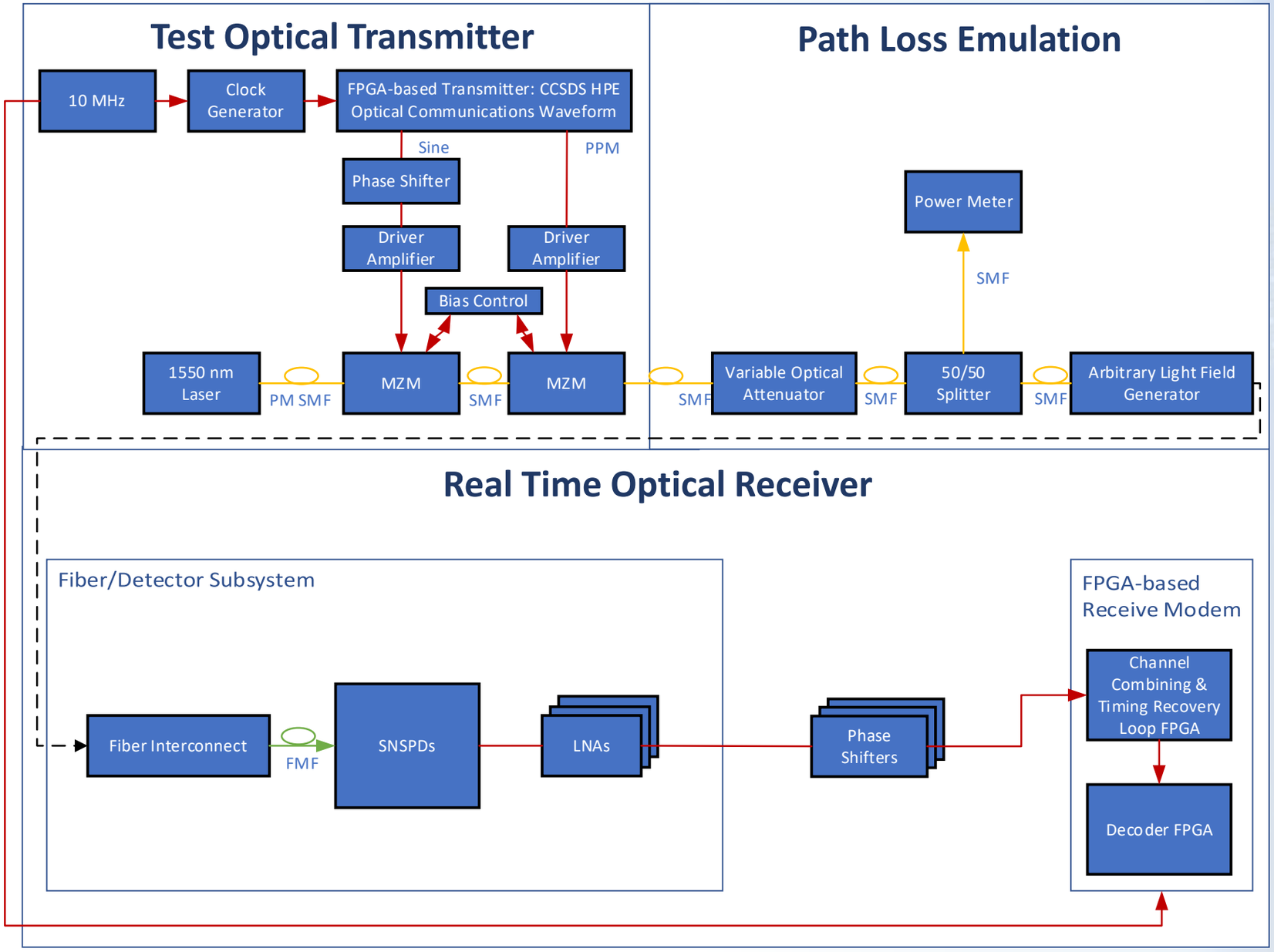
- **Xilinx Radio Frequency System-on-Chip (RFSoC) FPGA with 16 ADCs**
- **Time alignment with mechanical phase shifters**
- **Performs channel combining, photon counting, symbol timing recovery, codeword alignment, convolutional deinterleaving**
- **Calculates channel statistics to send to Decoder FPGA**

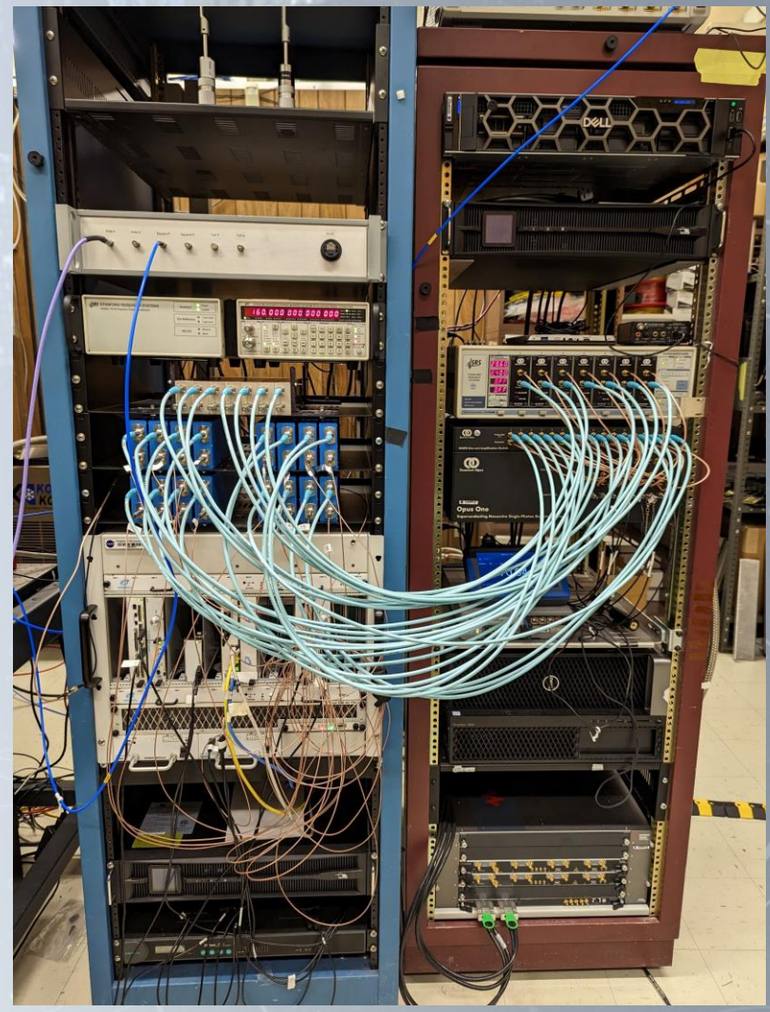
Decoder FPGA

- **Calculates 8-bit slot log-likelihood ratios**
- **Performs BCJR iterative decoding and queuing and reordering for multiple decoder instances**
- **Test mode allows independent characterization of decoder FPGA**



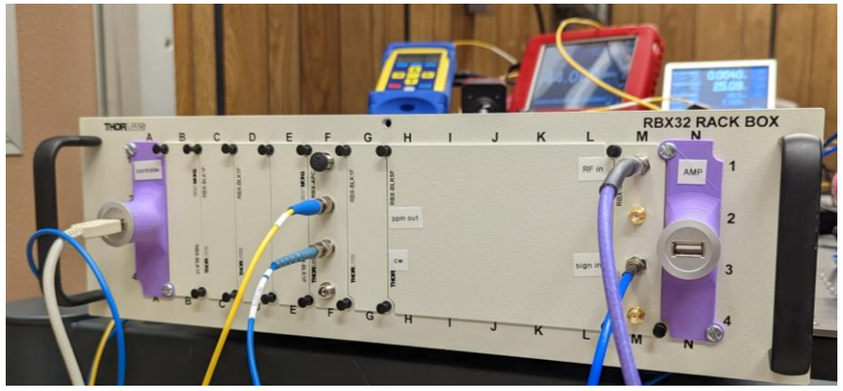
Test Setup

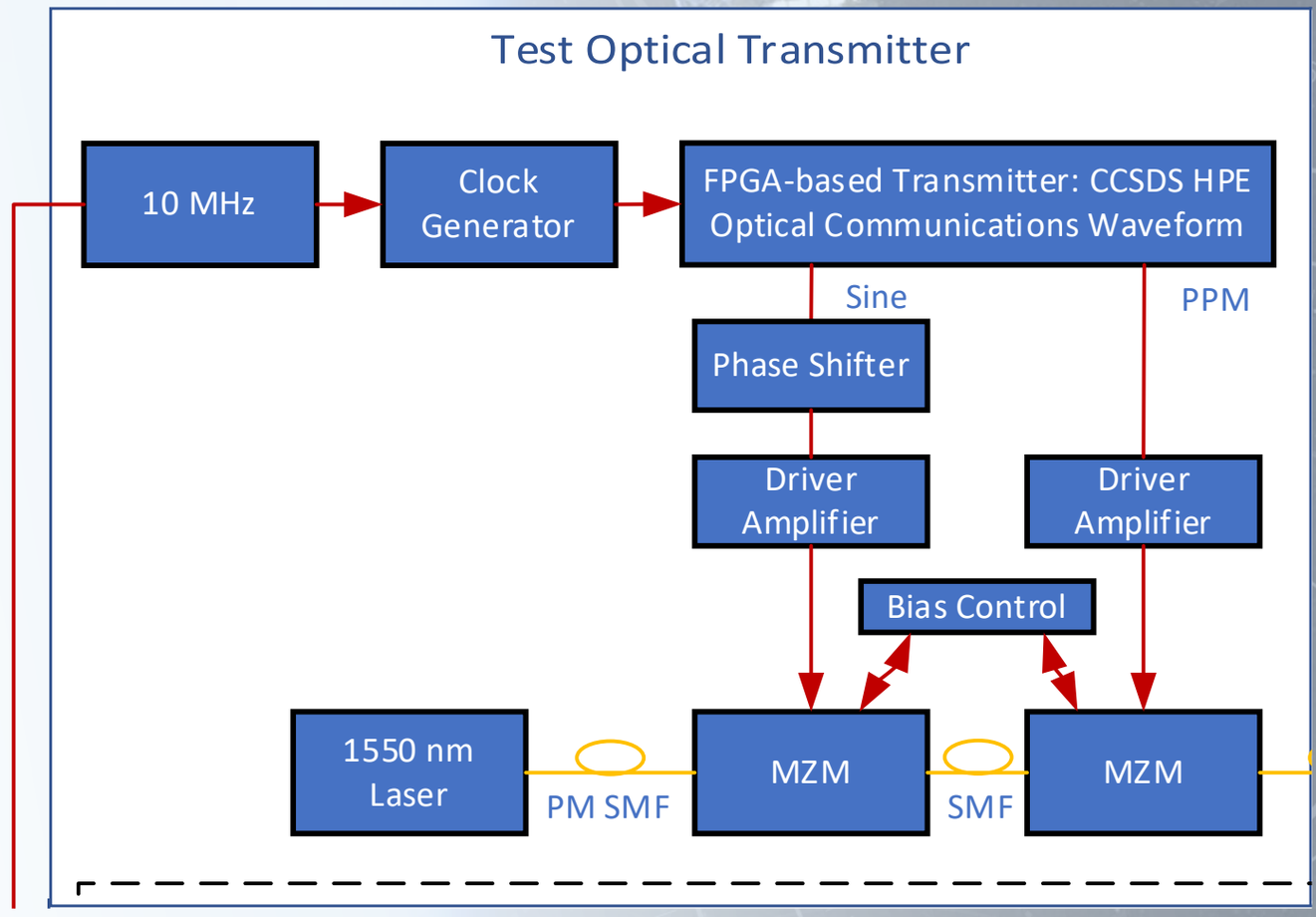

Test Optical Transmitter
10 MHz
Clock Generator
FPGA-based Transmitter: CCSDS HPE Optical Communications Waveform
Sine
PPM
Phase Shifter
Driver Amplifier
Driver Amplifier
Bias Control
1550 nm Laser
PM SMF
MZM
SMF
MZM
Path Loss Emulation
SMF
Variable Optical Attenuator
SMF
50/50 Splitter
SMF
Arbitrary Light Field Generator
Power Meter
SMF
Real Time Optical Receiver
Fiber/Detector Subsystem
Fiber Interconnect
FMF
SNSPDs
LNAs
Phase Shifters
FPGA-based Receive Modem
Channel Combining & Timing Recovery Loop FPGA
Decoder FPGA



Test Optical Transmitter

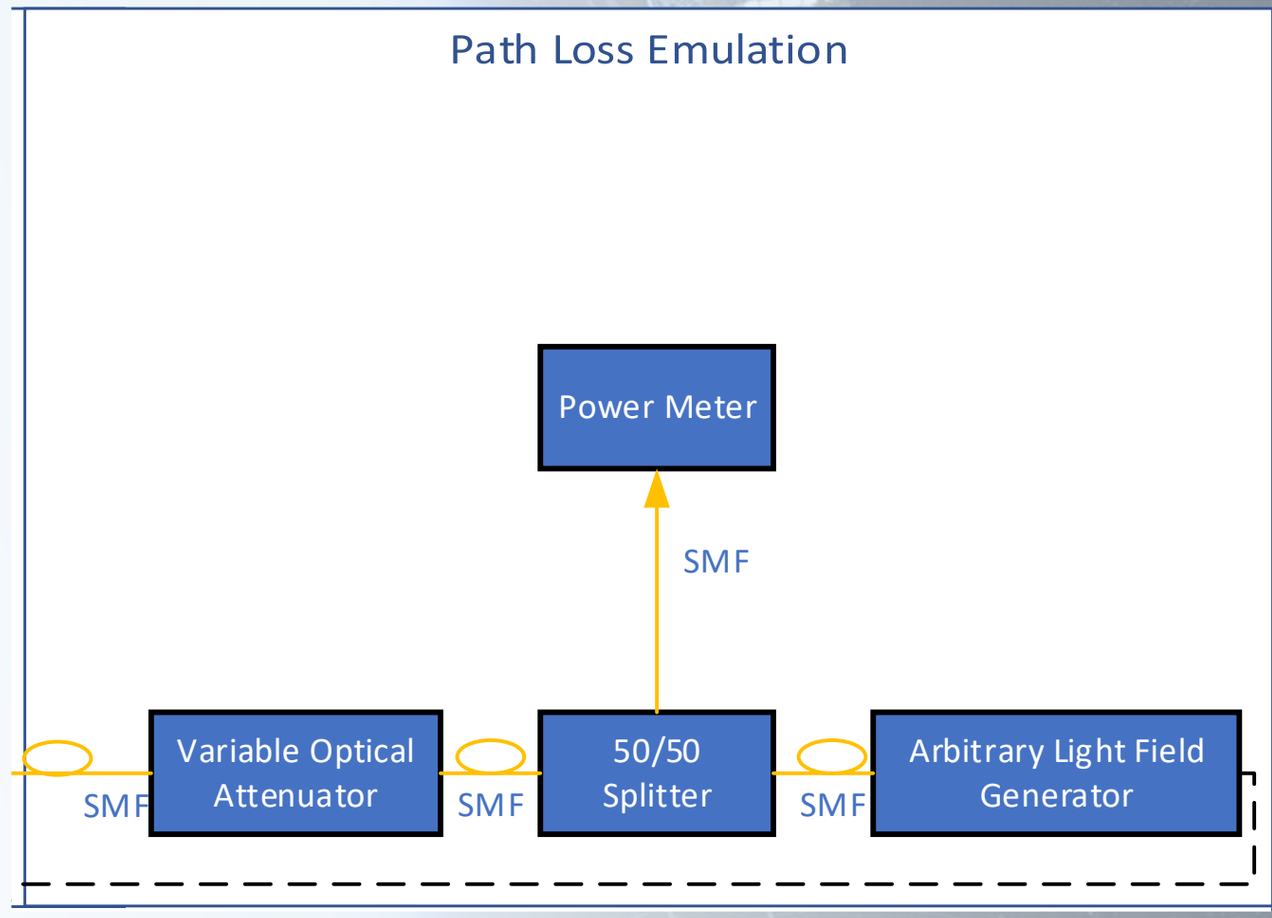
- **Sine and PPM signal generated by FPGA**
  - **Enables testing with Doppler Rate**
- **Pulse carving configuration implemented with 2 Mach Zehnder Modulators**
- **Bias controller algorithm:**
  - **Gradient descent with five-point stencil derivative**





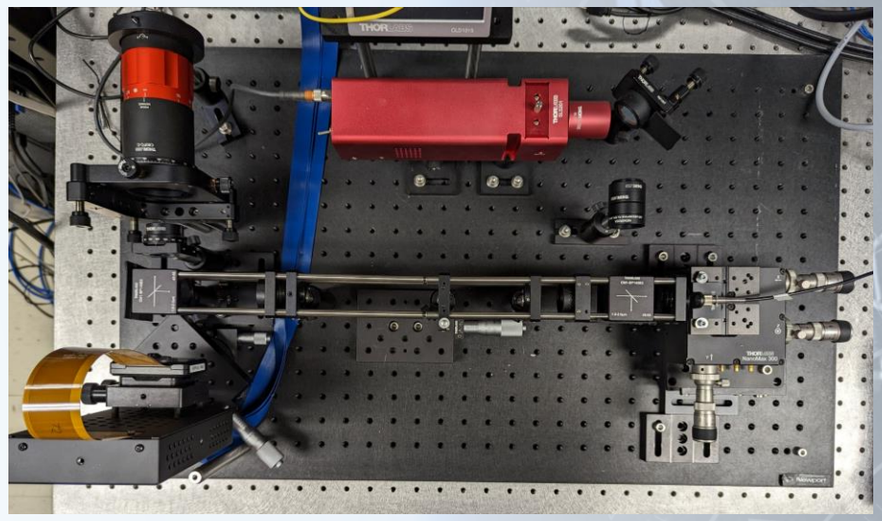
Path Loss Emulation

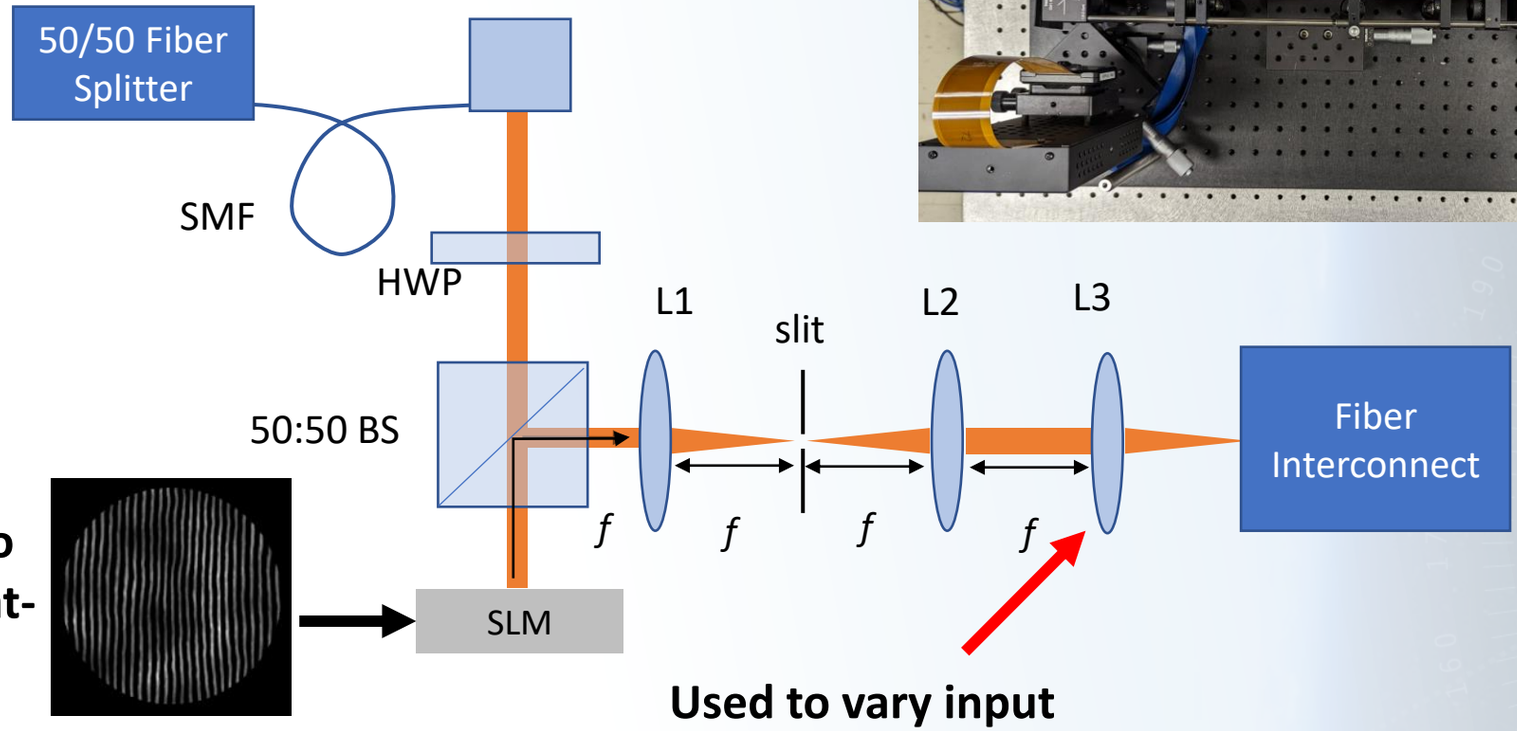
- VOA used for free-space path loss
- Arbitrary Light Field Generator: flat-top generated for input to the fiber interconnect
- Tests completed without added atmospheric turbulence
- Fiber/detector testing was completed with emulated atmospheric turbulence*



*Vyhnalek, B., and Tedder, S. "Fiber-detector subsystem loss comparison for a ground-based photon-counting optical receiver," Proc. SPIE Free-Space Laser Communications XXXV, 12413 (2023).

Arbitrary Light Field Generator



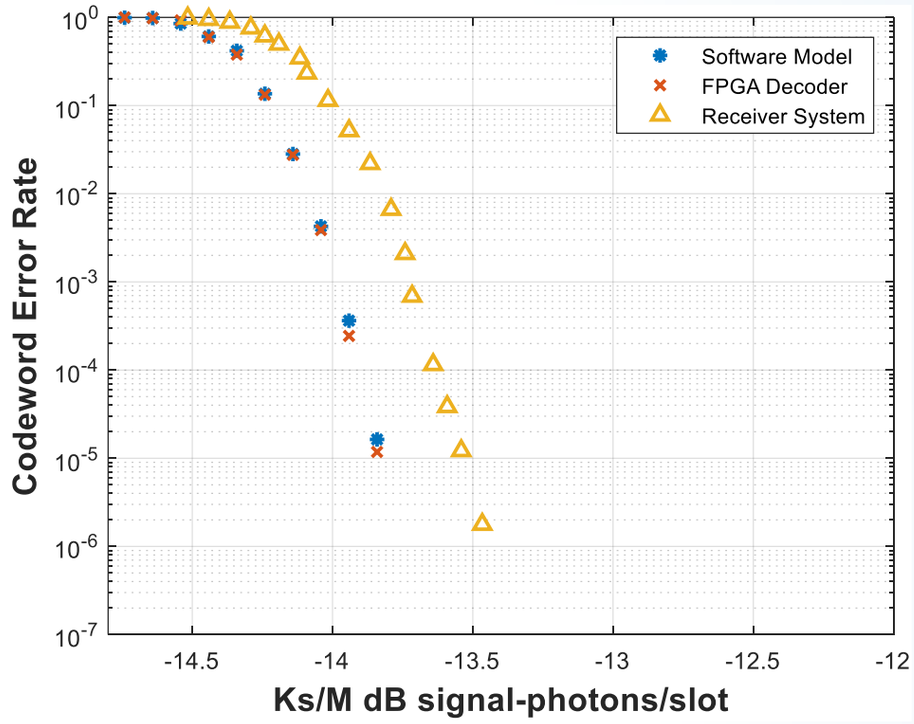


Hologram to generate flat-top beam

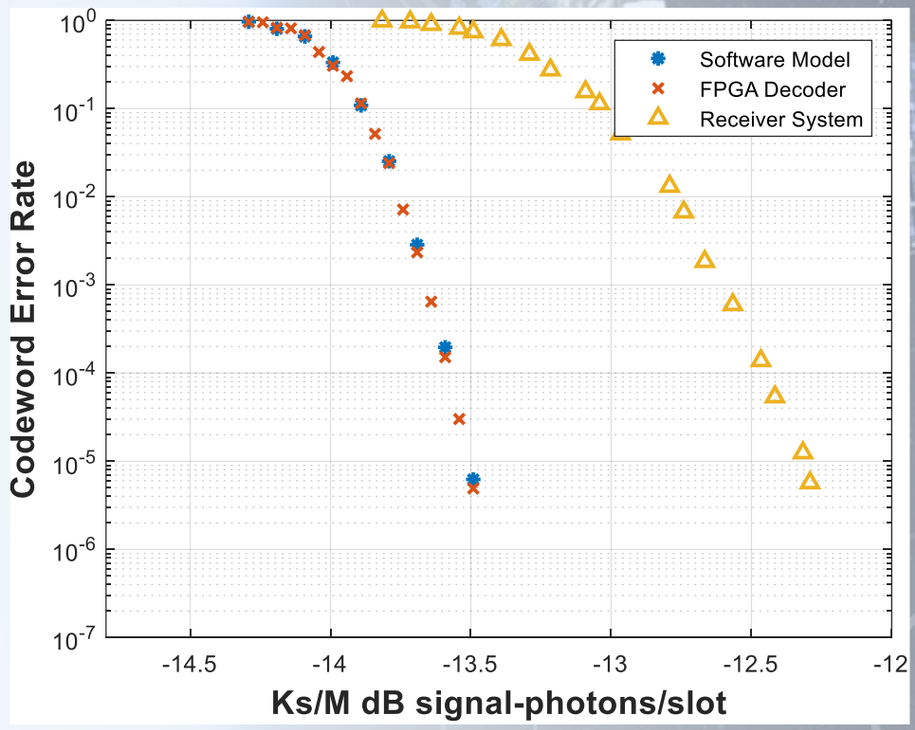
Used to vary input numerical aperture to Fiber Interconnect

Codeword Error Rate Curve Results – PPM-16, Code Rate 1/3, 133 Mbps

Photonic Lantern + 7 Single-pixel Detectors



FMF + 16-pixel Detector Array

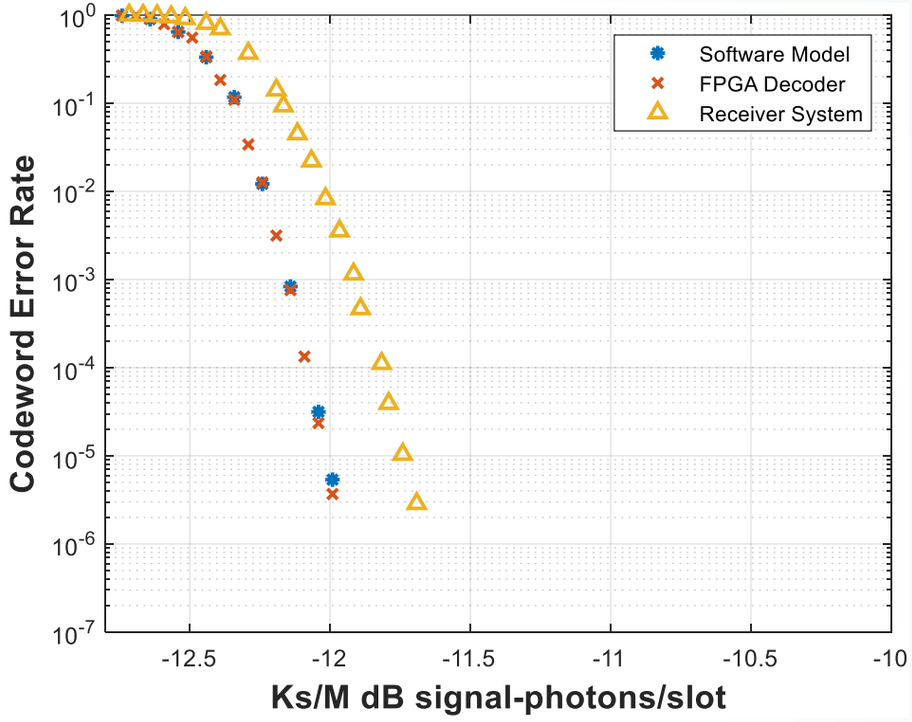


When operating where the photonic lantern numeric aperture is matched to turbulence conditions, it is expected that both architectures will perform similarly.

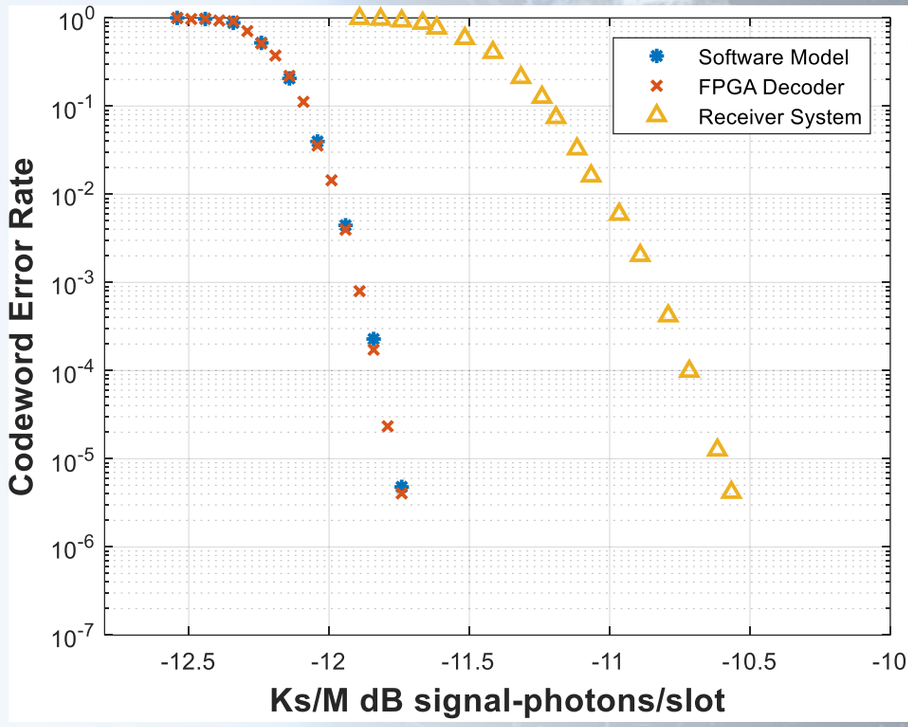
Detector Jitter & FPGA Implementation Loss (dB)		Fiber & Detector Loss (dB)		Measured K_b at 10^{-5} CWER (dB photons/slot)		Required Input Power at 10^{-5} CWER (dBm)	
PL	A	PL	A	PL	A	PL	A
0.3	1.2	8.0	3.2	-27.2	-22.0	-72.2	-75.5

Codeword Error Rate Curve Results –PPM-16, Code Rate 1/2, 200 Mbps

Photonic Lantern + 7 Single-pixel Detectors



FMF + 16-pixel Detector Array



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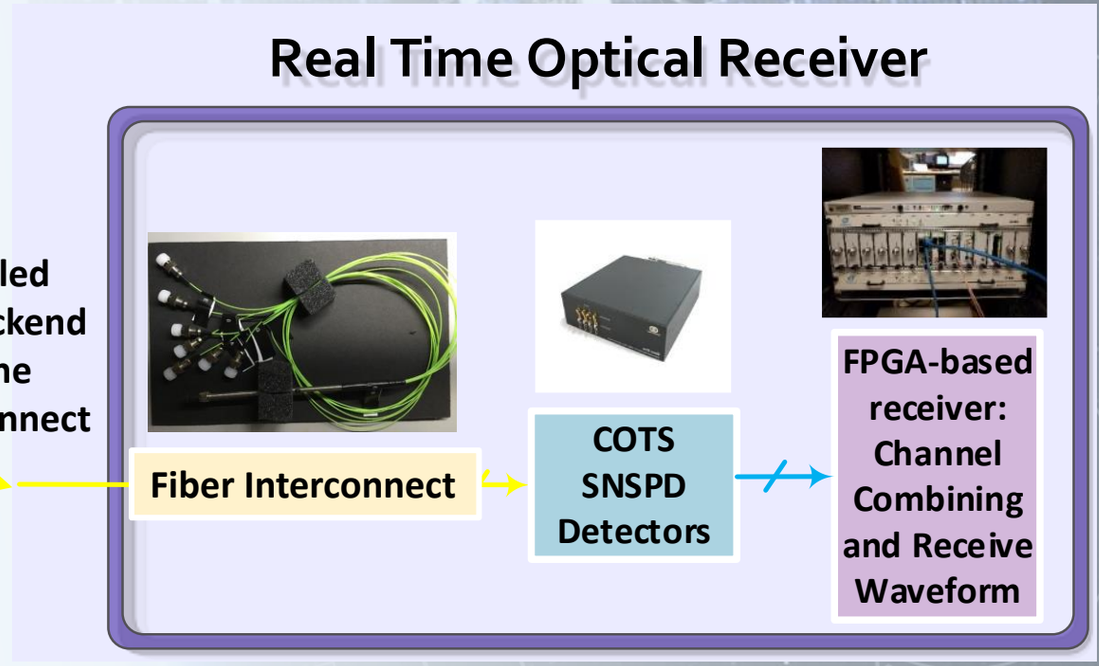
Detector Jitter & FPGA Implementation Loss (dB)		Fiber & Detector Loss (dB)		Measured K_b at 10^{-5} CWER (dB photons/slot)		Required Input Power at 10^{-5} CWER (dBm)	
PL	A	PL	A	PL	A	PL	A
0.3	1.2	9.6	3.5	-24.7	-20.8	-68.7	-73.5

Receiver will be demonstrated at the NASA GSFC Low Cost Optical Terminal*

Optical ground station components provided by NASA GSFC LCOT: dome, telescope, back-end optics (includes tracking and pointing)

Light is coupled from the backend optics into the fiber interconnect



*Lafon, R., Bai, Y., Caroglanian, A., Dailey, J., Desch, N., Garon, H., Hall, S., Miller, R., Paulson, D., Safavi, H., Sekulic, P., Speer, J.,Thompson, P., and Wu, V. "NASA's low-cost optical terminal (LCOT) at Goddard Space Flight Center," SPIE Free-Space Laser Communications XXXV, 12416 (2023).

Conclusion

- **A photon-counting ground receiver has been developed and tested for several CCSDS HPE modes.**
  - **Two fiber/detector architectures were prototyped**
- **When operating in an optical ground station where the photonic lantern numeric aperture is matched to turbulence conditions, it is expected that both architectures will perform similarly.**

Thank You!

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